The time-space structure of pulses in Cherenkov light detectors

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***Abstract*. Here the results of calculations of pulses in Cherenkov light detectors for the Yakutsk array are presented. As long as the Vavilov-Cherenkov light is used to calibrate signals in scintillation detectors at the Yakutsk array it is vital for these measurements to be precise. The validity of measurements of the signal $Q(400)$ used as the estimation parameter at the Yakutsk array has been confirmed. Our calculations show that the width of time pulses increases from nearly 50 ns at a distance of 100 m from the shower axis up to 700 ns at 1000 m.**

***Keywords*: Vavilov-Cherenkov light**

I. Introduction

It is a known problem of calibration of energy estimations of extensive air showers (EAS). At the Yakutsk array the Vavilov-Cherenkov light is used to calibrate signals in scintillation detectors [1]. Although our calculations show that for the same flux of Vavilov-Cherenkov light there should be much higher signals in scintillation detectors than it is measured in the experiment [2].

First, this contradiction may have different explanations. The hadron interaction model may not correctly describe the real processes at high energies. This question will be probed at LHC once it is operational. Alternatively, we may have a different chemical composition of primary cosmic rays – all our calculations were undertaken in the assumption of light chemical composition at high energies. Although recent experiments claim that the primary particles at those energies are protons [3], [4] (with exclusion of [5]).

Each detector array encounters the problem of full signal registration. Each detector after being triggered by some event (a particle hits the detector, the counting rate exceeds some level, a signal comes from another detector, etc.) collects the signal for some period of time, a so-called time gate. Time gates should be wide enough to collect possibly all particles coming to the detector. On the other hand, since we always have a background from low energy cosmic rays or the local sources (radioactivity, light pollution, etc.), the time gates should not be too wide in order to keep the signal to noise ratio high enough. So the time gates should be of about the disk thickness. At most detector arrays such as Haverah Park, Volcano Ranch, Yakutsk, the time gates were set to about 2 μs.

A. Watson in [6] suggested that the time gates at the Yakutsk array are too narrow to detect all particles and thus the signals are underestimated, that leads to an overestimation of energy of the primary particles. A rapid change in steepness of the measured lateral distribution functions of signals and the fact that some of the showers detected at Haverah Park had signal width more than 2.2 μs [6] are claimed to support this suggestion.

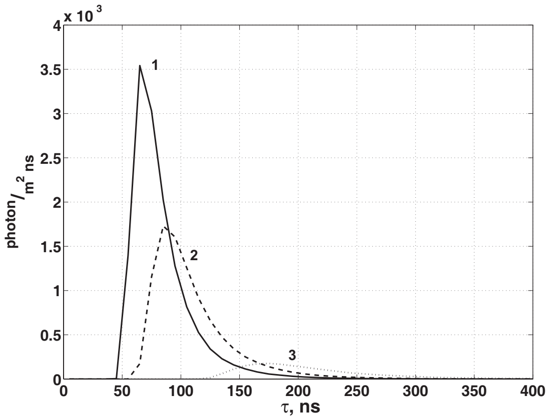

Fig. 1: Pulses of Vavilov-Cherenkov light at 400 m distance from the shower axis. Showers induced by primary gamma with energy 10 GeV starting from different depth (solid curve 1 – 350 g/cm^2, dashed curve 2 – 550 g/cm^2, dotted curve 3 – 750 g/cm^2)

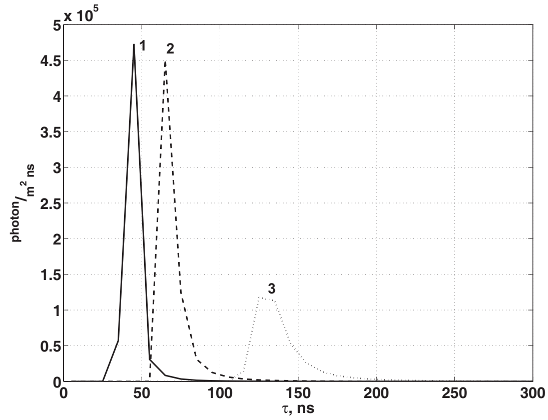

Fig. 2: Pulses of Vavilov-Cherenkov light at 400 m distance from the shower axis. Showers induced by primary electron with energy 316 MeV starting from different depth (solid curve 1 – 350 g/cm^2, dashed curve 2 – 550 g/cm^2, dotted curve 3 – 750 g/cm^2)

In our previous paper [7] we have studied the problem

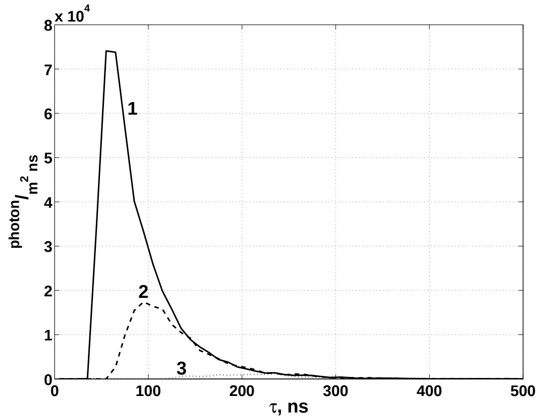

Fig. 3: Pulses of Vavilov-Cherenkov light at 400 m distance from the shower axis. Showers induced by primary muon with energy 10 GeV starting from different depth (solid curve 1 – 350 g/cm^2, dashed curve 2 – 550 g/cm^2, dotted curve 3 – 750 g/cm^2)

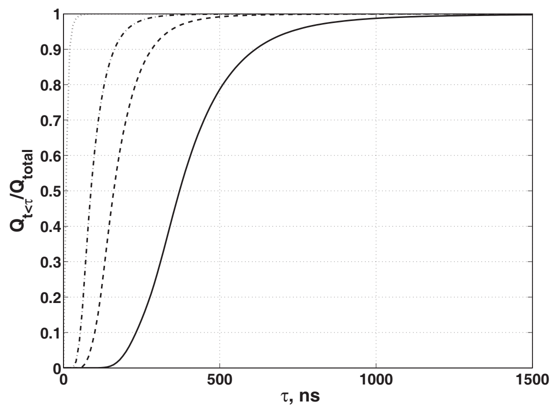

Fig. 4: Fraction of Vavilov-Cherenkov light collected within time τ at the different distances from shower axis (doted curve – 100 m, dash-dotted curve – 400 m, dashed curve – 600 m, solid curve – 1000 m)

of form and width of pulses in scintillation detector. In a few words though the signals in scintillation detectors at large distances from the shower axis (more than 1 km) exceed 2 μs (at 600 m signal width is well within 2 μs) and only part of the signal is measured the difference between the theory and the experiment is still too high to be explained solely by partial signal measurements. Therefore, additional analysis was required. In this paper we investigated another question – the form of the Cherenkov light pulse at the detector.

II. Method of simulations

As well as in the previous work in this study we used CORSIKA 6.500 [8] with QGSJET-II [9]–[13] for high energy and Gheisha-2002d [14] for low energy calculations. Parameters of the atmosphere and the magnetic field were set to fit the conditions of the Yakutsk array. The time delay of arrival of the Vavilov-Cherenkov photons was calculated as the time between its arrival at the observation level and the time of arrival of the very first particle at the observation level. All calculations were carried out in the framework of a multilevel hybrid scheme [15], i.e. we calculated the database of Vavilov-Cherenkov light pulses at different distances from the shower axis from low energy showers from primary electrons, gamma and muons (some examples are shown in Fig. 1–3) and using source functions (also calculated in our previous simulations [7]) we calculated the impulses for high energy showers.

Source function describes the number of particles with energy in interval $[E; E+dE]$ born in the atmosphere at depth $[x; x+dx]$. The database of the Vavilov-Cherenkov light pulses $C_{e,\gamma,\mu}(\tau, r, E, x)$ describes the Vavilov-Cherenkov photon flux from a shower induced at depth x by electron or gamma or muon with the energy E at the distance from the shower axis r at moment of time τ. Time starts with the arrival of the very first particle at the observation level. Having the analytical source functions of low energy particles from ultra high energy shower and databases of the Vavilov-Cherenkov light pulses from low energy showers one can calculate pulses from ultra high energy shower:

$$
\begin{aligned}
F(r,\tau) = & \int\limits_0^{x_0} dx \int\limits_{E_{min}}^{E_{thr}} S_e(E,x) C_e(\tau, r, E, x) + \\
& + \int\limits_0^{x_0} dx \int\limits_{E_{min}}^{E_{thr}} S_\gamma(E,x) C_\gamma(\tau, r, E, x) + \\
& + \int\limits_0^{x_0} dx \int\limits_{E_{min}}^{E_{thr}} S_\mu(E,x) C_\mu(\tau, r, E, x).
\end{aligned}
$$

Here E_{thr} - some reasonable maximum energy threshold, maximum energy of particles in source functions; E_{min} - some low energy threshold (naturally in case of the Vavilov-Cherenkov light for electrons and gammas it is 21 MeV, for muons - 4 GeV); $S_{e,\gamma,\mu}(E,x))$ - source functions of electrons, gammas and muons respectively. But if the source functions were obtained numerically as a table of parameters (energy E_i, depth of generation x_i and weight w_i if thinning procedure was applied) of low energy particles generated in the shower than this integral converts to a sum:

$$
\begin{aligned}
F(r,\tau) = & \sum_i w_i C_e(\tau, E_i, x_i, r) + \\
& + \sum_j w_j C_\gamma(\tau, E_j, x_j, r) + \\
& + \sum_k w_k C_\mu(\tau, E_k, x_k, r).
\end{aligned}
$$

After all theese calculations for vertical showers from primary protons we obtained the following results.

III. Results

In Fig. 4 the fraction of Vavilov-Cherenkov light collected within time τ at different distances from the shower axis is shown. As one can see the width of the Vavilov-Cherenkov light impulse at the distance of 100 m from the shower axis is less than 50 ns, at 400 m – 200 ns, at 600 m – 400 ns and at 1000 m it is less than 1 μs. Therefore, the time gates at the Yakutsk

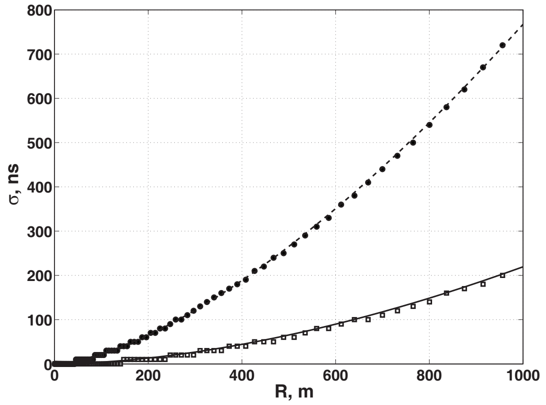

Fig. 5: The Vavilov-Cherenkov light forefront (squares) and backfront (circles) and their approximations

array detectors are set wide enough to collect all of the Cherenkov photons from EAS, thus in the experiment the Vavilov-Cherenkov light is measured correctly.

In addition we have calculated the form of the Vavilov-Cherenkov light forefront and backfront (see Fig. 5). As the forefront arrival time we took the moment when 5% of total signal is collected and the backfront was considered as the moment when 95% of all Cherenkov photons were collected. We found that the best fit is achieved by the power function $\sigma = a \cdot R^b$ (with $a_f = 1.63 \cdot 10^{-3}$, b_f= 1.71, $a_b = 3.95 \cdot 10^{-2}$ and b_b= 1.43 for forefront and backfront respectively) rather than with a spherical front.

IV. Conclusion

The width of the Vavilov-Cherenkov light pulse does not exceed 1 μs at the distance of 1000 m from the shower axis. Therefore, at the Yakutsk array all the Cherenkov photons from EAS are collected and the time gates of the Cherenkov detectors may be set even lower.

Cherenkov light forefront and backfront may be approximated by a power function $\sigma = a \cdot R^b$ (with $a_f = 1.63{\cdot}10^{-3}$, b_f= 1.71, $a_b = 3.95{\cdot}10^{-2}$ and b_b= 1.43 for forefront and backfront respectively) with a better accuracy than with a spherical front.

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